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# Experimental Analysis of Thermal Fields Surrounding Horizontal Cylindrical Geothermal Exchangers

Iacopo Golasi[a,*], Ferdinando Salata[a], Massimo Coppi[a], Emanuele de Lieto Vollaro[b], Andrea de Lieto Vollaro[a]

[a] *"Sapienza" University of Rome, via Eudossiana 18, Rome 00186, Italy*

[b] *"RomeTRE" University of Rome, via Vito Volterra 62, Rome, 00154, Italy*

**Abstract**

In the engineering field there are many applications where it is important to evaluate the heat exchange between cylindrical surfaces and the surrounding ground (horizontal geothermal exchangers for heat pumps, underground pipelines, underground electric cables, etc...). For these reasons, there is an increased interest in the correct analysis of the soil thermal resistance. In this study different types of soils with linear heat sources were considered and, through a physical model reproduced in laboratory, the thermal field was evaluated. The model reproduced an "undisturbed" portion of soil and the influence of different thermal conditions of the linear heat sources and of the environmental parameters were evaluated. This paper will be extended through the implementation of the experimental device into a numerical model by applying a calculation software to the finite volumes; the result is a predictive model of the soil resistance able to furnish accurate information of the real mean radial thermal resistivity surrounding the geothermal exchanger.


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Keywords: ground heat exchangers, linear thermal source, soil, experimental setup, thermal conductivity.

## 1. Introduction

Among those engineers dealing with the air conditioning in buildings meant for civilians, there is a growing interest in the exertion of the soil as a heat source during the winter and as a heat sink in the summertime. The authorities' effort to make the planners aware of the necessity of performing buildings

* Corresponding author. Tel.: +39-0644585661; fax: +39-064880120.
*E-mail address:* iacopo.golasi@uniroma1.it.


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energy optimization determined a major focus on different and alternative types of plant systems respect to those currently used. Particular attention was given to technical solutions characterized by the combination of heat pumps (whether they are saturated steam compression or absorption operating units) with geothermal exchangers which allow to the GSHP (Ground-Source Heat Pumps) to work with highly performative values, thus becoming more competitive than other systems solutions. This type of technology, while exploiting the ability to store and use heat in the first layers of the subsoil, has the possibility to function without interruptions and without being affected by the meteorological conditions of outdoor environment [1].

Saturated steam compression GSHP were put on the market in the '60 and '70 and at first were divulgated in the countries of Northern Europe, followed by North America and finally China. Right now those countries claiming the 55% of the power installed in the whole world are China, USA, Sweden, Turkey and Japan while those trends presenting a higher growth characterize United Kingdom, Korea, Ireland, Spain and Netherlands [2]. It is necessary to consider that these technologies also have a bright future ahead: the GSHP, based on absorption devices, respect the energy requirements set by nZEBs (near Zero Energy Building) [3-6].

The propagation of these systems technologies [7], even if supported by an established industrial production, is not completely accepted by the planners who shows some doubts concerning the real effectiveness of the soil heat exchange phenomenon. One of the problems is that soils present different configurations and thermal characteristics that do not ensure an accurate valuation of the heat exchange conditions in geothermal systems. This is why it is important to investigate the heat exchanges occurring through underground exchangers and the soil surrounding them, in order to provide information to the planners for a proper dimensional estimation of these devices. This paper focuses in particular on the evaluation of the soil thermal resistance surrounding the exchangers formed by a pipe closed circuit system placed horizontally.

## 2. Description of the experimental device

The experimental device has the goal to simulate the operating conditions of a single probe set horizontally for the soil heat exchange [8] thus permitting the analysis of those thermal quantities characterizing the soil around the linear heat source (Fig.1).

Fig. 1 – Picture of the experimental device reproduced in the laboratory.

The model is formed by a wooden box which reproduces, in scale, a soil section where there is a steel pipe with an electrical conductor without a powered insulating sheathing. The pipe simulates the presence of an exchange geothermal probe in the soil. The box is a parallelepiped made of wood whose length is of 1.9 m, width 1.5 m and height 0.35 m. The upper part is open and is filled with materials simulating the soil; the five sides delimiting it laterally and on the side of the floor are formed by wood panels whose thickness is of 0.02 m (Fig.1). The inside of the box is painted with an impermeable enamel to avoid a transfer of humidity between the box and the surrounding environment. In order to prevent a direct contact with the laboratory floor, a layer of polystyrene was placed under the box thus isolating it thermally. The whole experimental device is placed in a thermostated environment (where there is the possibility to adjust the inside temperature with an accuracy of ± 1K), devoid of windows and isolated from the outside.

Right on the axis of symmetry of the major side of the box, placed between the ground and at a depth of 15 cm, it was reproduced a trench whose width is 0.08 m representing the excavated area where the geothermal probe is installed. A linear thermal source is simulated thanks to a stainless steel pipe with a diameter of 5·10-3 m, a thickness of 0.5 mm and a length of 1.5 m located over the sand bed at a depth of 0.135 m respect to the ground level.

At the extremities of the electrical cable placed inside the steel pipe (exposed to an electric potential difference thanks to a system of sample resistances forming a Wheatstone bridge) it is possible to make the power circulate. Due to the Joule effect the result is a controlled pipe heating process, thus simulating the behavior of a geothermal probe where a hot fluid circulates.

With such device it is possible know both the potential difference at the extremities of the electrical cable functioning as a heater and the intensity circulating, and it is possible to determine, in an accurate way, the heat dissipated by the conductor in the steel pipe towards the surrounding soil [9,10].

The area of the soil which is part of the installed trench over the pipe is the easiest way to let the heat released to the outside environment. This is why such zone was monitored from a thermal point of view with five K thermocouples (Chromel (Ni-Cr) (+) / Alumen (Ni-Al) (-)), placed at a same distance of 25 mm. 25 more "K" thermocouples are located in the box outside the trench excavation (with three different depth values). Thanks to these thermocouples the result is a complete mapping of the soil filling the formwork. In this way the thermal field surrounding the heat source can be reproduced. Even the steel pipe simulating the electrical cable presents a thermocouple as the one previously described which measures the temperature reached due to the Joule effect. The thermocouples cold junction is immersed in a thermostated bath with an accuracy of 0.1 K.

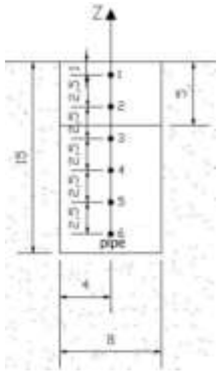


Fig. 2 – Detail of the thermocouples placed in the excavated area and how the steel pipe is positioned.

The data supply and acquisition system is formed by: an electric generator, a computer, two resistors in parallel (model S650) of 1.75 ohm and a sample resistance (Rc = 0.1 Ω at 20°C). The electrical conductor is supplied electrically by an uninterrupted power supply stabilized electric generator providing a variable voltage ranging between 2 V and 15 V. The voltage drop, ΔV, at the extremities of the pipe has a range of 1.8 ÷ 2.8 V. The electricity going through the pipe is estimated by measuring the voltage drop at the extremities of a sample resistance with a high accuracy (rp = 0.1 Ω ± 0.00001 Ω). The data acquisition system is a 34970A DATA model HP AGILENT [11]. Every thermocouple is connected to proper slots located in the acquirer; the resulting output is the ΔT between the cold junction (the temperature is known) and the soil temperature. Thanks to a serial port, the acquirer is connected to a computer which, besides allowing through a software to start the measurement process, permits to sample and store the digitized/scanned temperature values of every thermocouple in a certain period of time. The multimeter measurement error for the thermocouples output signal equals to a maximum of ± 4 mV. Each thermocouple provided values with an accuracy of ± 0.2 K, in a temperature range of 273 K and 373 K. The total error of measurement, calibration error included, is of ± 4 % (as shown by equation 2).

The box, in the section reproducing the undisturbed soil, is filled with a clayey and compact compound (expanded sifting clay) whose thermophysical characteristics are known. The filling material, used to simulate the soil installed around the linear heat source, is river sand sieved and dried at a temperature of 80 °C for 8 hours, whose thermal conductivity value is measured. The thermophysical characteristics of the filling materials are showed in Tab. 1. Their density and thermal conductivity were measured complying with the IEE Standard 442-1981-1996 and ASTM D-5344-00 by using specific instruments (MAE A5000T + Thermal conductivity probe: MAE CTS-45) with a maximum accuracy of ± 5%.

Tab. 1 - Thermophysical characteristics of the materials used in the experimental device.

| Material | Density $\delta$ [km/m$^3$] | Specific Heat $c_p$ [kJ/(kg K)] | Thermal Conductivity $\lambda$ [W/(m K)] |
|---|---|---|---|
| Sand | 1,700 | 837.2 | 0.35 |
| Clay | 380 | 840 | 0.29 |

To make an experimental estimation of the soil resistance, once the system had stationary conditions, 4 different measurements were carried out. To be more specific the system was furnished with a power supply able to provide each linear meter of the pipe with a heat q of 8, 10, 13, 18 W/m [12]. The system was considered stationary after a period of time of 6 hours that is without any value variations of the thermocouple registering a pipe temperature higher than ± 0.2 K.

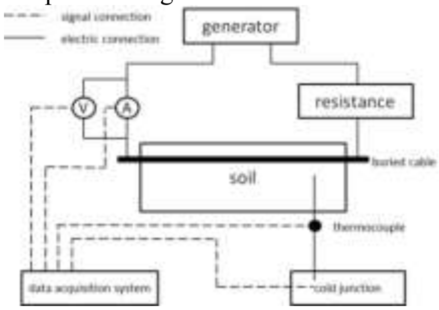


Fig. 3 – Measurement chain of the experimental device realized in the laboratory.

The soil resistance is estimated as [13]:

$$R_{exp} = \frac{T_t - T_{air}}{q} = \frac{(T_t - T_{air}) r_p I_t}{V_r V_t} \quad (1)$$

Hence the maximum differential error for what concerns the measurement chain (Fig. 3) is:

$$\frac{\delta R_{sper}}{R_{sper}} = \frac{\delta T_t - \delta T_{air}}{(T_t - T_{air})} + \frac{\delta r_p}{r_p} + \frac{\delta I_t}{I_t} + \frac{\delta V_r}{V_r} + \frac{\delta V_t}{V_t} = \pm(0.033 + 10^{-6} + 3.6 \cdot 10^{-4} + 0.0035) \cong \pm 3.7\% \quad (2)$$

Such value is considered satisfactory for the accuracy required to the experimental measures.

## 3. Trench configurations for the installation of the underground exchanger and experimental results.

To simulate different soil configurations above the linear heat source installed, three different configurations of the underground excavated area were arranged: the first 0.03 m of the soil stratum (starting from the underground level) are formed by materials presenting different physical characteristics: Case A; sand; Case B: polystyrene; Case C: concrete. All the data referring to stationary measurements. Tab. 2 shows these values of the thermal conductivity of the materials used and the materials thickness in the three cases studied experimentally. This is why it was carried out a measurement campaign of 18 different measures by changing the amount of electric power circulating through the wire placed inside the pipe which simulates the underground heat source, that is the heat generated by the Joule effect and released into the soil.

Tab.2 – Values of the thermal conductivity and thickness of the materials used for the roofing of the excavated area.

| Material | Thermal conductivity λ [ W/mK ] | Thickness s [m] | | |
|---|---|---|---|---|
| | | Case A | Case B | Case C |
| Concrete | 1.10 | - | - | 0.03 |
| Polystyrene | 0.04 | - | 0.03 | - |
| Sand | 0.35 | 0.15 | 0.12 | 0.12 |

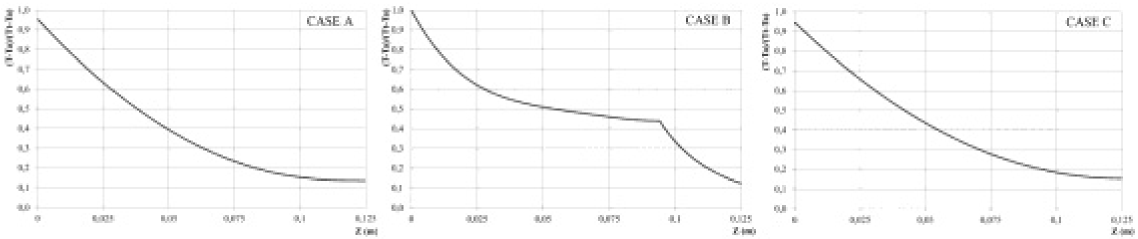


Fig. 4 – Graphs of the normalized temperatures respect to the temperature of the environment in each of the 3 experimental cases.

Fig. 4 shows the graphs representing a comparison of the temperatures, complying with the standard temperatures normalized respect to the temperature of the outside environment and measured by the thermocouples placed between the pipe and the external surface of the soil as showed in Fig. 2. These graphs report the trend of the temperatures in each Case (A-B-C). It can be noticed how in every case examined there is a drop in temperature characterizing the closest material around the pipe.

## 4. Conclusions

Thanks to the experimental device realized, it is possible to have a proper examination of the heat transfer, in the excavated area, of the geothermal cylindrical exchangers placed horizontally. Through an analysis of the experimental measures and the trend of the temperatures, it can be noticed how the soil stratum, with the highest drop in temperature, is the one closest to the pipe, whereas if the distance from the pipe increases the temperature change presents a more gradual trend. This phenomenon means that it is important to pay particular attention while choosing the filling material used in the trench of the excavated area around the exchanger. In conclusion, it seems important to examine in a more accurate way these studies in order to realize predictive model to plan the underground exchangers which take into consideration the thermophysical properties of the surrounding soil and that can be used for a planning considering real installation conditions of such exchangers. This is why the model here reproduced in a laboratory will be reconstructed as a numerical model through a calculation software to the finite volumes and used for its validation.

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## Biography

Iacopo Golasi achieved in March 2014 the Master of Science with honors in Mechanical Engineering from the University of "Roma Tre" and he is Ph.D. student in "Energy and Environment" in the DIAEE of the University of Roma "Sapienza" since November 2014. He is co-author of several scientific papers published in international journals or presented at conferences.The biography of the corresponding author. (50 words)